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Review

Hybrid nuclear-renewable energy systems: A review

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ABSTRACT

Climate change and energy security have emerged as the biggest concerns of the present century. Renewable energy sources are not continuous, dependent upon geographical location as well as climatic conditions, and require a very large land footprint. Future of nuclear energy is also uncertain because of public apprehensions and subsequent government policies. To overcome the issues derailing these two virtually carbon-free energy sources, a new hybrid or integrated nuclear-renewable energy system is being proposed and seen as an attractive option. Such integrated energy systems are conceived as a nuclear power reactor coupled with renewable energy generation and industrial processes that may simultaneously tackle the concerns regarding grid flexibility, climate change, energy security, optimal return on invested capital, and settling public concerns. Apart from highlighting the key challenges associated with nuclear energy and renewable energy sources while operating as an independent power generation system, the present paper delineates the various aspects associated with integrated nuclear-renewable energy systems. It may be speculated that integrating nuclear energy and renewable energy into a single hybrid energy system, coupled through informatics linkages, would enable to overcome the demerits present when they operate individual.

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1. Introduction: the energy question

Energy is an intangible currency essential for sustaining the life. More than one billion people are expected to be added in coming 15 years, making world population about 8.5 billion in 2030 (Melorose et al., 2015). Energy consumption is anticipated to increase by 34 percent till 2035. Nearly one-third of expected increase in the energy consumption will be the result of rapidly rising global population and world economy. The major portion of the global energy demand is achieved from the conventional sources of energy for long. It is forecasted that conventional fuels will remain the central source of energy driving the global economy— satiating approximately 60 percent of the energy consumption increase and accounting for around 80 percent of total energy consumption in 2035; as illustrated in Fig. 1 (British Petroleum, 2017). Although coal slows and renewables advance in the next two decades, the increase in combined contribution of oil and gas in global energy production will follow trend similar to that of the last two decades. The trend of overdependence on fossil fuels for energy production is threatening the sustainability of life itself. Fossil fuels are not only unevenly distributed and depleting fast but also tampering the ecological balance necessary for existence (Upadhyay and Sharma, 2014). Climate change and energy security have emerged as the biggest concerns of the present century. It is now well accepted that unless far-reaching steps are taken to moderate global warming, economic development will be slowing and world could move towards human made environmental disaster (Apergis et al., 2010; Menyah and Wolde-Rufael, 2010; Sudhakara Reddy and Assenza, 2009; The Stern Review on the Economic Effects of Climate Change, 2006). The presence of a huge share of fossil energy sources in unstable region of the Middle East poses risks and raises concerns for different nations in terms of the dependability of energy supply and pricing (Gnansounou, 2008). Ecological challenges and concerns about energy security are compelling many nations to explore energy options other than fossil fuels. Both nuclear energy and renewable energy—virtually carbon-free energy sources—have emerged as promising solutions for ecological degradation and energy security problems. Consequently, many countries have started investing in nuclear and renewable energies as a means to a) reduce dependency on crude oil trade, b) ensure better energy security, c) curtail the price instability associated with foreign fossil fuels, and d) mitigate ecological degradation (Toth and Rogner, 2006; Vaillancourt et al., 2008). Few countries— which were uncertain about nuclear energy in the past— are also displaying a lot of inclination for developing nuclear reactors now in order to diversify sources of energy supplies, strengthen energy security, and deliver a carbon free alternative to conventional fuels (Adamantiades and Kessides, 2009). There are currently 447 nuclear power plants in operation worldwide and 287 new ones are coming on line (including 28 in Japan) by 2035 ("World Nuclear Association," n.d.). However, the future of energy is not so bright. Nuclear and renewable energies have their own issues. Renewable energy is not continuous, dependent upon geographical location and climatic conditions, and it requires a very large land footprint. Even though nuclear energy is a proven technology for generating electricity, many environmental groups and public have considered it unattractive since long. Such unfavourable attitudes and apprehensions are due to the possibility of accidents leading to meltdown of nuclear reactors. Meltdown of reactors has catastrophic social and environmental impacts. Lack of clear policies and regulations regarding the disposal of radioactive nuclear waste, and risk of fissile nuclear fuel being used for destructive purposes if diverted to radical groups add fuel to public fear (Adamantiades and Kessides, 2009).

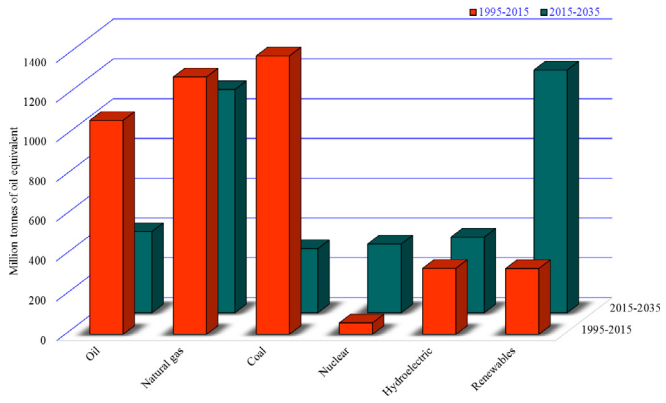

Fig. 1. Change in contribution of different sources in global energy production.

There are drawbacks and risks associated with any power generation method. A sense of optimisation among energy wants, economic growth, safety, and sustainability has to be struck since each type of energy source has its own trade-offs. In light of reaping the benefits of both nuclear energy and renewable energy sources by attenuating their individual demerits, a new nuclear-renewable integrated energy system has been at the forefront of the wider issue of the energy debate. The objectives of the present article are to briefly highlight the drawbacks and challenges associated with both nuclear and renewable energy systems while operating independent and critically evaluate the hybrid renewable-nuclear energy systems. Renewable energy systems are seldom questioned while integrated nuclear-renewable energy systems are relatively new phenomenon; that is why it is expected that this review article will provide crucial understanding and contribute to the ongoing debate of sustainability.

2. Challenges for renewable energy

Renewable energy is the energy obtained from natural and persistent flows of energy occurring in the immediate environment (Twidell and Weir, 2015). Presently, power generation using renewable sources of energy stands well poised to fulfil new electricity requirement of the world. Renewable energy —accelerated by policies and strategies directed at reducing environmental degradation and enhancing energy security with sustainability— expanded at its fastest rate to date in 2014 and presently contributes above 45 percent of total energy additions. Extensive deployment of renewables continues to excel in energy-starved emerging economy and few nations such as China and India have ambitious plan. Furthermore, rapid progress in technology, growth of newer markets with better resources, and strengthening of financing scenario by government policies are enabling more cost-effective installation of dynamic renewable technologies like solar photovoltaics, solar-thermal plant, and onshore wind worldwide (International Energy Agency, 2015). However, there are various issues and challenges associated with it as discussed in subsequent sub-sections.

2.1. Scalability, commercialisation, and timeline

Scalability refers to the capability of a system or source to accommodate surge in production or number of users without a penalty in cost, performance, reliability or functionality. Alternative energy sources must be scalable within a fixed time frame at a competitive cost in order to be primarily dependent on them for power generation. Various non-conventional energy sources like thin-film solar, algae-based diesel, cellulosic ethanol etc. have been

successfully verified at the small scale, however, such laboratory-scale verifications do not speak about the potential for applicability of these technologies for energy production at a large scale. Another concern is about taking the science from laboratory to the market or the question of time gap in which the proposed alternative source of energy will get commercialised completely. Any power generation technology takes lot of efforts and time to see the light of the market— procedures require to be standardised and optimised, grant for patents are filled, pilot or trial plants are constructed and appraised, and their ecological impacts are evaluated. The typical time frame between laboratory demonstration of feasibility and full large-scale commercialisation of power production is 20–25 years (Kirpotin, 2012). In the meantime, the energy requirement dynamics change and the exponentially piled up energy demand is tried to fulfil with conventional sources, thus making a vicious circle.

2.2. Material input requirements

Renewable energy sources are not only about high initial capital investment but also resources and materials for the sustained growth of its infrastructure. The type and quantity of the raw materials required may even limit scalability, affect the cost, commercialisation, and feasibility of any alternative energy source. Uninterrupted supply of rare-earth materials to support the emerging technologies relevant to energy is particularly important. For example, palladium, platinum, and rare-earth materials are needed for the manufacturing of fuel cells. Indium and gallium are required for solar-photovoltaic technology. Lithium is an integral component of advanced batteries. Rare-earths material like gallium and indium are required even for energy saving technology, such as organic light-emitting diode or light-emitting diode. In case of large scale integration of such energy alternatives, there will be a huge stress to obtain these rare-earth materials. Thin-film solar, for example, has been endorsed as a highly cost effective, more flexible, and with wider applicability for solar to electricity conversion compared with older silicon panel technology. Thin-film solar technology utilises indium due to its unique characteristics at present, however, it is also extensively used as an element of flat-screen display monitors. There are limited known reserves of indium, and a report based on study conducted in 2007 predicted that at present rate of consumption, it would last just for thirteen years more (Cohen, 2007). A recent study has also suggested that shortage of minerals used in electric car batteries including indium, gallium, and lithium could trigger trade wars (Ferrè et al., 2002). Table 1 provides an estimation of raw materials demand for sustaining emerging technologies relevant to energy generation globally (Marscheider-Weidemann et al., 2016). In order to match such a huge surge in the requirement of rare-earth materials, there is a need of finding new deposits or sources of these acute metals. Moreover, novel techniques for excavating the rare elements from various types of rocks are pressing need as extraction techniques of rare metals are not fully standardised and recognised yet (Ferrè et al., 2002).

2.3. Intermittency and land foot print

Renewable energy sources are dependent upon geographical location, climatic conditions, and require a very large land footprint. Moreover, they do not produce power consistently and continuously. However, the need of present world is continuous power. The present world cannot do with varying or fluctuating electricity, that too at the cost of large land footprint. Irregularity of renewable energy sources such as solar and wind poses a key hurdle to their extensive integration with the present grid infrastructure (Rugolo and Aziz, 2012). Capacity factor—average percentage of time for which any power plant is operating at its full rated capacity annually —is a quantitative indication of challenges due to intermittency in electricity generation. As mentioned in Table 2, capacity factor of solar photovoltaic systems is only 12–19 percent and it is around 30 percent for wind systems. In contrast, a nuclear power plant generates electricity with a capacity factor of more than 90 percent which is comparable to a coal-thermal power plant (70–90 percent) in the United States (Kirpotin, 2012). Moreover, the land requirement and other key data based on sustainability and economical-environmental indicators for power generation (provided in Table 3) reveal that renewable energy sources have enormous challenges before becoming the chief power generating source (Brook and Bradshaw, 2015). For instance, almost 50 percent of the total energy need of United States could be fulfilled utilising renewable energy technologies if these are properly developed and realised, however, approximately 17 percent of the United States' land resource would be needed for it (Pimentel et al., 2002).

Table 2
Typical capacity factors for power generation.

Type of power generation	Capacity factor (%)
Photovoltaics	12–19
Solar thermal	~15
Solar thermal with storage	70–75
Wind	20–40
Hydropower	30–80
Geothermal	70–90
Nuclear reactor	60–100
Coal thermal	70–90

Table 1
Global demand of raw materials for emerging technologies relevant to energy generation.

Raw material	Fraction of world production in 2013		Emerging technologies relevant to energy generation
	2013	2035	
Gallium	0.30	0.40	Thin-layer photovoltaics, white LEDs
Neodymium	0.80	1.70	Permanent magnets, laser technology
Indium	0.30	0.50	Thin-layer photovoltaics
Scandium	0.20	1.40	Solid oxide fuel cells
Platinum	0.00	0.60	Fuel cells, catalyst
Cobalt	0.00	0.90	Lithium-ion batteries, synthetic fuels
Palladium	0.10	0.50	Seawater desalination
Copper	0.10	0.30	Efficient electric motors
Selenium	0.00	0.11	Thin-layer photovoltaics
Ruthenium	0.00	0.03	Dye-sensitised solar cells

Table 3
Data and relative ranking of power generation options on sustainability and economic–environmental impact indicators.

Indicator (per TWh)	Coal		Natural gas		Nuclear		Biomass		Hydro		Wind (onshore)		Solar (PV)	
	value	rank	value	rank	value	rank	value	rank	value	rank	value	rank	value	rank
GHG emissions (t CO_2)	1001000	7	469000	6	16000	3	18000	4	4000	1	12000	2	46000	5
Electricity cost ($ US)	100.1	4	65.6	1	108.4	5	111	6	90.3	3	86.6	2	144.3	7
Dispatchability	A	1	A	1	A	1	B	4	B	4	C	6	C	6
Land use (km^2)	2.1	3	1.1	2	0.1	1	95	7	50	6	46	5	5.7	4
Safety (fatalities)	161	7	4	5	0.04	1	12	6	1.4	4	0.15	2	0.44	3
Solid waste (t)	58600	7	NA	1	NA	1	9170	6	NA	1	NA	1	NA	1
Radiotoxic waste	mid	6	low	3	high	7	low	3	trace	1	trace	1	trace	1
Weighted rank	–	6.0	–	2.0	–	1.3	–	6.7	–	3.3	–	2.3	–	5.3

2.4. Compatibility and technological barriers

Since renewable energy sources are intermittent in nature with relatively low capacity factor (see Table 2), the prerequisites to transport this fluctuating electricity are extensive. Variable nature of renewable energy sources constrains its integration with conventional grids for transportation of produced electricity. Even though concepts like smart grid— an electrical network which is intelligent enough to increase efficacy, flexibility, sustainability, dependability and safety of an electrical system by monitoring and controlling the grid with help of automation and full integration (Kabalci, 2016; Tuballa and Abundo, 2016)—or energy storage (Ho et al., 2016; Speidel and Bräunl, 2016) are attempting to resolve the substitutability issue, these concepts have their own problems (Colak et al., 2016; Kim et al., 2016; Kyriakopoulos and Arabatzis, 2016). (Colak et al., 2016) conducted a detailed survey of the critical challenges in smart grids in terms of information and communication technologies, sensing, measurement, control and automation technologies, power electronics and energy storage technologies. It was reported that the information and communication technologies of smart grids face the challenges of deliberate attacks caused by industrial espionage and terrorists as well as the inadvertent compromises due to user errors and equipment failures. The design, deployment and maintenance challenges in smart metering, how to design demand management and control, the uncertainties in the generation profile of distributed and renewable generation resources and the unbalance between user requirements and energy saving in energy management systems are few key challenges in control and automation technologies of smart grids (Kim et al., 2016) argued that, apart from the development in the technologies, it is necessary to build up an active policy plan for the dissemination of the smart grid. It is also required to reform current electric pricing systems in order for the smart grid to induce a decrease in electricity consumption. A strong scheme for publicity and information on the smart grid is necessary to maximise its reduction effect on electricity consumption. Renewable energy also has compatibility issues with present infrastructure and to tap its benefits to the maximum, advanced technology and/or new infrastructure erection are required which in turn exponentially increase the capital and land footprint (Shaker et al., 2016; Urzúa et al., 2016). For example, in spite of ethanol being capable of getting blend with gasoline and used directly, it is not possible to transport ethanol through existing pipeline infrastructure as it is highly susceptible to absorb water and has much higher oxygen content. Developing an alternative pipeline infrastructure for its transportation and increasing its usage would require technological advancement and huge cost (Sorate and Bhale, 2015).

2.5. Ecological issues

Renewable energy sources are subjected to few subtle hurdles which prove more detrimental to ecosystem in comparison to degradation caused by conventional sources at many instances. Renewable resources are considered to be inexhaustible based on the reasoning that these can be recycled, but it should not mean that these are practically infinite and do not undergo degradation (Nuclear Energy in a Sustainable Development Perspective, 2000). Even renewable resources, for example land, water, air, are vulnerable to stresses because of various practices which may be irreversible. Water and air are vulnerable to contaminants due to simplicity with which they can be used as free resources for receiving and dispersing waste. Similarly, land which acts as habitat for various animal and plant species is extremely sensitive to environmental degradation, and can be destroyed easily. Thus, renewable resources need to be perceived as finite, susceptible to stresses and degradation. Such degradation is intricately associated with public perspective for any energy sources to be accepted fully. For example, in spite of the advantages of hydroelectric power plant, it is also found to be the reason of various environmental problems. The stored water often encroaches valuable fertile land and alluvial bottomland. Furthermore, dams affect the existing species like aquatic plants, fishes, microbes, and many others in the ecosystem (Ligon et al., 1995; Pimentel et al., 2002). Tampering of ecosystem by dams may significantly reduce the fish species in river systems (Brown and Bauer, 2009). In case of wind farm, installing the wind turbines in or in vicinity of flying path of migrating bird species or other wildlife may cause their collision with the rotating blades or supporting infrastructure. The total wind turbines erected in the United States only has caused death of around 300 birds per year (Kerlinger et al., 2010). Rotation of wind turbine produces high decibel noise and this is unavoidable problem of its functioning (Katinas et al., 2016). The emergency release or accidental leakage of toxic chemicals utilised in the heat transfer or storage system of solar-thermal power plant is also seen as potential environmental hazards. Decline in water level may also be a cause of concern especially in arid regions (Pimentel et al., 2002). The use of poisonous compounds, such as cadmium sulfide and gallium arsenide, in the manufacturing of solar-photovoltaic systems is a major environmental problem (Bradley, 1998). Since these highly toxic substances remain in the environment for years, dumping and recycling of non-functional solar-photovoltaic cells present a major challenge. Even in the case of biofuel, there is a debate on the use of land resources for food or fuel since long.

High initial capital investment along with risks associated with it is a major obstacle for big utilities in order to enter the market aggressively. Dramatic dips in conventional fuel prices in past years

have also raised concerns regarding the competitiveness of alternative sources. For growing markets, policies and regulations, financing conditions and grid infrastructure can present obstacles to growth. What will be the fate of renewable— will falter or could a rapid expansion can take place—only time can dispel the cloud.

3. Challenges for nuclear energy

Nuclear power plants are capable of providing consistent and carbon-free base-load electricity. These plants do not discharge any greenhouse gas during operation and comparatively require very less land footprint, see Table 3. Presently, nuclear power plants fulfil over 11 per cent of the world's electricity demand and there are more than 60 nuclear reactors under construction in various countries at present (Suman et al., 2016; 2015b). In spite of being a proven technology and an attractive option for power generation in order to progress towards a green world, nuclear reactors have not progressed rapidly and accepted widely because of various issues and challenges. Some of the major challenges are as follows:

3.1. Economic and financial

If nuclear power has to become dominant in quenching the future energy-thirst, countries must erect new nuclear plants not only as replacement of those on the verge of completing their service time but also to considerably increase the number of operational reactors. However, contrary to forecasts made by government and industrial experts few years back, cost of constructing a new nuclear plant has risen steeply and it is huge compared to the other low-carbon alternatives. Typically, the cost of any technology decreases with increase in its production volume, scale factors, and with passing of time due to technological learning. The unexpected increase in the cost of erecting a nuclear plant has been understood essentially as an exception that echoes the idiosyncrasies of the regulatory mechanism influenced by worldwide growth in public opposition, stringent regulations, and delayed construction period. The need of colossal financial investment combined with concerns involved in construction and delay in licensing too have escalated the cost of commissioning nuclear plants (Chu and Majumdar, 2012; Hultman et al., 2007). Present average construction cost estimate of $9 billion per plant impedes the growth of nuclear as well as threatens the financial investment viability of many companies (Podobnik, 2006). Moreover, public perspective, policies and regulation, and government initiatives are inclined to renewable sources. Most often, cost of power produced from heavily subsidised renewable energy is compared with nuclear energy.

3.2. Safety and security

Safety—primarily in terms of effects of radiation on living animal and environment—and security concerns about the attack by terrorists as well as potential of non-civilian use of nuclear are the key arguments used against nuclear energy. The mishaps at Fukushima, Chernobyl, and Three Mile Island are often cited in order to build public apprehensions or opinion regarding the safety issues. The Fukushima nuclear accident on March 11, 2011 in Japan has severely dented the prospects of growth of civilian nuclear power in many countries, Table 4 reflects the changes made in nuclear policy by different countries after Fukushima. The claim of nuclear power industry made in last decade about next generation nuclear reactor to be 'inherently safe' has died down. Design of latest generation of nuclear reactors are still susceptible to release of radioactive fuel to environment because of accidents, sabotage or radical attack. Use of recycled radioactive fuel for next generation of reactors, which lot of pro-nuclear scientist still advocate, would increase the risk of fissionable fuel being misused to develop nuclear weapons. Moreover, the distrust and fear triggered by a nuclear catastrophe would threaten the sustainability of the whole nuclear power technology (Kuramochi, 2015; Ming et al., 2016; Podobnik, 2006; Srinivasan and Gopi Rethinaraj, 2013).

3.3. Waste disposal

Even though there is an on-site infrastructure in form of concrete casks to store the nuclear waste for the short period, having a well charted plan for long-term disposal of radioactive nuclear waste is crucial for the wide acceptance and substantial growth of nuclear industry. Despite the hazards and risks posed by radiological waste, no facility yet exists anywhere in the world for the disposal of spent or decayed radioactive nuclear fuel and other high-level radiological wastes. In spite of the fact that nuclear power industry is six decade mature, there is not even a single long-term waste repository licensed by any nation. Even after spending more than $13.5 billion of taxpayers, one such proposed long-term waste repository at Yucca Mountain site in Nevada has been impaired because of political, technical, and managerial problems (Beswick et al., 2014; Podobnik, 2006). With the advancement of relevant technology, few alternative ways like deep borehole disposal are emerging but they are far from realisation at present (Beswick et al., 2014).

3.4. Research needs

There are various aspects of nuclear power demanding researchers' attention, ranging from developing new inherently safe reactor to designing a secure waste management system. To gain insight into next generation of nuclear reactors, may be based on fusion rather than fission, there are needs to invest both in basic research and infrastructure required for the research. Developing novel materials which can withstand the harsh environment of nuclear reactor core—combination of high irradiation fluence or energy, high temperatures, and pressures— pose a major challenge to materials scientist. Presence of limited facility for understanding the effects of high fluence irradiation on materials worldwide is one of the significant technological limitations in developing the structural materials for next generation nuclear reactors as well as

Table 4
Changes in nuclear policy post-Fukushima.

Core agenda		Country
Expansion	Using and also constructing new reactors	USA, Russia, China, France, India
	Using and plan to construct new reactors	Mexico, Brazil
	No operational plant but constructing reactors	Chile, Egypt
	No operational plant but plan to build reactors	Iran
Status quo	Using with no new plant construction	Japan, Spain
Phase-out	Using but slowly going to decommission all	Germany, Belgium, Switzerland
Phase-down	Using but planning to restrict the numbers	Sweden

for concept of fusion energy. The number of research reactors having fast fluence fission facility is decreasing and there is no high flux neutron irradiation facility for fusion reactors (Ekins, 2004; Zinkle and Was, 2013). In addition, even expanding the present nuclear power reactors would require the construction of many new uranium fuel enrichment plants as well as infrastructure for spent fuel repositories (Podobnik, 2006).

3.5. Public perception and opinion

Post Fukushima, public acceptance has become a key factor in the process of nuclear technology deployment. The immediate aftermath of the Fukushima disaster witnessed dramatic shifts in public opinion. In a poll conducted across 23 countries after Fukushima, only 22 percent was in the favour of nuclear energy expansion while 30 percent asked for an immediate shutdown. In another poll conducted in France— which derives around three-fourths of its electricity from nuclear power reactors—more than 77 percent of the sample responses wished for either rolling down or immediate shut down of the nuclear power plants. More or less, globally similar public opinion has played a crucial role in dramatic change in energy policies adopted by governments or regulatory agencies. Perhaps the most appalling decision was taken by Germany to shut down the seven of their older nuclear power reactors immediately and to phase out the other nine nuclear reactors by 2022. The federal council of Switzerland, a country which is dependent on nuclear reactors for almost 40 percent of its electricity, decided for a slow decommissioning of nuclear reactors in May 2011. It has planned to shut down the first nuclear power plant by 2019 and completely become independent of nuclear reactors by 2034 (Birmingham Policy Commission, 2012). Strong and unremitting protest for a long period by the People's Movement Against Nuclear Energy (PMANE) organisation against Kudankulam nuclear power plant, India also reflects the attitude of common people worldwide towards nuclear power. Similar sentiments were echoed in other countries too (Ertör-Akyazı et al., 2012; Tampakis et al., 2013). In a broad sense, the breach of public trust after Fukushima accident is anticipated to cause deceleration of nuclear power plants expansion worldwide for long.

4. Hybrid nuclear-renewable energy systems

Use of renewable energy technologies at local or household level can immensely contribute to socio-economic development of any nation. For example, solar heater for household purposes or drying of agricultural products, solar lamp for night school, solar cooker for cooking, mini wind turbine for pumping drinking water or irrigating farm, biogas for decentralised cooking or electricity and many more applications can enrich the quality of life drastically even in rural and remote areas not connected to grid (Flavin and Hull Aeck, 2005). The use of solar power in routine activities is also being promoted (Suman et al., 2015a). However, fluctuating or intermittent nature of renewable causes lack of its compatibility with present electrical grid infrastructure and poses serious concerns over its deep penetration and large-scale power generation.

Nuclear power is a reliable carbon-less base-load electricity generation source. Although, it was concluded in a recent study that Fukushima could have been prevented with effective nuclear regulatory system and accidents like this are unlikely in a country with strict regulatory mechanism (Wang et al., 2013); anti-nuke policies and public opinion over safety and waste disposal are the biggest hurdle for its expansion.

Perhaps, the global energy demand would not be achieved by nuclear alone, but it may not be get achieved without it (Abu-Khader, 2009). A future pathway for the global energy mix that emphasises only renewable resources and opposes the large-scale deployment of nuclear power will inevitably increase negative economic and environmental impacts (Hong et al., 2015). Despite its controversial reputation, nuclear power is sustainable, efficient and reliable, and various studies argued that it must be part of the energy mix (Augutis et al., 2015; Brook et al., 2014). Formulating an integrated methodology—combining technical, economical, and energy security perspectives— to evaluate the optimal share of various energy sources, Augutis et al. (Augutis et al. (2015) reported that share of renewable sources should be 50 percent while nuclear technology should contribute 30 percent to the total energy production; remaining should be derived from natural gas. Strong social acceptance of renewable sources and higher steady rate operation of nuclear reactors can be combined in hybrid energy systems to overcome the issues associated with their independent use.

4.1. Types of hybrid system

Depending upon various factors like geographical, economical, desired form of output etc. different renewable energy sources may be coupled to form a nuclear-renewable hybrid energy system; Table 5 mentions few of the possible integrated systems (Keller, 2011; Richard et al., 2011; Ruth et al., 2014).

Fig. 2 shows a hybrid nuclear-solar power plant based on the patented technology of Keller (2011). It uses a nuclear reactor to heat a compressed working fluid that is expanded within turbines rotating compressors of both reactor plant and air pressurising plant. Heat exchangers are used to extract low-grade heat from the working fluid and transfer to the moisture removal equipment located in downstream side of air compressing plant. In addition, inter cooler heat exchangers are used to further cool the working fluid prior to entry into the compressors, thereby reducing compressor power needs. A regenerative heat exchanger is used to pre-heat the working fluid before its re-entry into the reactor by extracting low grade heat from the working fluid discharged from the turbines. In another few studies (Borissova, 2015; Popov and Borissova, 2017a; 2017b), a new type of hybrid nuclear-solar power plant having small modular nuclear reactor and concentrated solar-thermal plant is analysed. In this proposed hybrid energy system, the solar heat is transferred to nuclear steam to raise its temperature. Continuous superheating is provided through thermal energy storage. The results from design point calculations show that solar superheating has the potential to increase nuclear plant electric efficiency significantly, pushing it to around 37.5%.

Table 5
Examples of integrated nuclear-renewable system.

Energy sources		Coupling method	Storage method	Possible outputs
Nuclear	Wind energy	Electrical	Hydrogen	Electricity, hydrogen
Nuclear	Solar energy	Thermal	Thermal	Electricity, heat
Nuclear	Biomass	Thermal	Chemical	Electricity, biofuels
Nuclear	Geothermal	Thermal	Thermal	Electricity, heat
Nuclear	Wind energy and natural gas	Electrical and thermal	Chemical	Electricity, chemical products, synfuel

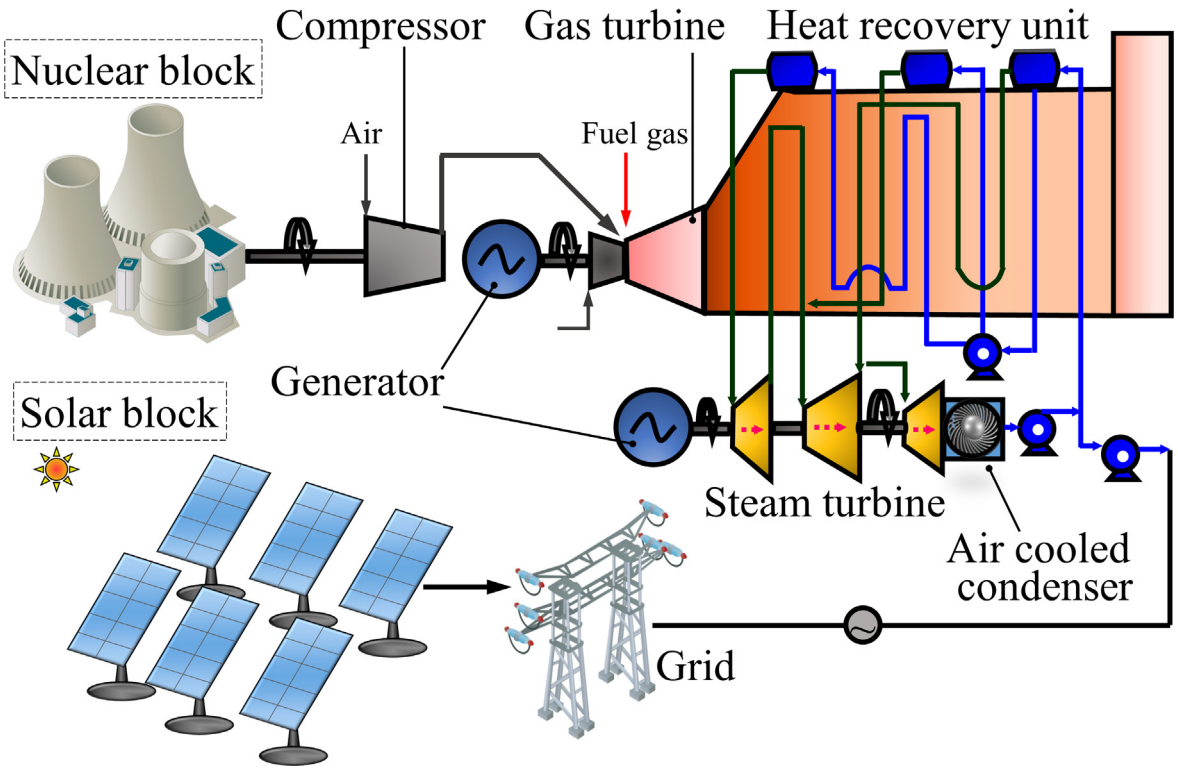

Fig. 2. Hybrid nuclear-solar energy system.

Solar heat to electricity conversion efficiency reaches unprecedented rates of 56.2%, approaching the effectiveness of the modern combined cycle gas turbine plants. In addition, substantial decrease of solar island investment cost is reported. Fig. 3 illustrates a hybrid nuclear-geothermal energy system patented recently (Richard et al., 2011). This hybrid energy system includes a geothermal system having a power plant, a pumping station, and a nuclear plant. Pumping station is used to inject fluid from reservoir through an injection well into the bedrock or hot dry rock zone which is sucked up through a secondary bore or extraction well coupled with conventional steam power plant. As fluid is injected into the bedrock, drop in temperature occurs due to heat transfer to the fluid, and this drop is compensated with the help of nuclear reactor whose core is positioned within bores in the hot dry rock zone. Another concept of wind farm integrated with a hybrid small modular reactor-biomass having a hydrogen production is recently developed (Papaioannou et al., 2014). The nuclear unit produces thermal power at its full capacity continuously and there is a provision of switching its heat output between the generation of steam for electricity production and biomass production unit. The integrated nuclear-wind energy system is operated in accordance with electricity demand, that is the sum of their electrical output is enough to satisfy the variation of electricity need. The hydrogen production unit needs electricity and operates on the surplus power generated during the peak wind farm performance.

4.2. Aspects of interconnections

It is expected that proposed nuclear-renewable hybrid systems will continue to operate component technologies similarly to how they have been operated independently. Thus, key technical issues will involve interconnections and few additional system issues due to the complexity of integration. Fig. 4 mentions some of the important interconnections and challenges they pose (Ruth et al., 2014).

Thermal interconnections are at heart of nuclear-renewable energy system in order to efficiently use the generated heat during low demand of electricity. Thermal energy storage reservoirs may be needed to soften the imposition of rapid transitions on the thermal hydraulics systems. Additionally, new remote flow monitoring system, control valves and pumps for high-temperature thermal hydraulic fluids, gases, molten salts, liquid metals, and ultra-supercritical steam will be needed. High-temperature heat circulation in aggressive environments associated with high-temperature steam, molten salts, and gases requires validation of metallurgy and possibly new heat-exchanger fabrication techniques (Adee and Guizzo, 2010). Research and development is also required to make hybrid energy systems respond rapidly, efficiently, and safely to electricity market signals. Successful electricity interaction will need development of advanced, interconnected sensing and informatics systems which identify all the needs and provide information to the control systems, thus enabling control systems to optimise profitability. In addition, advanced power electronics are necessary. They need to be of low cost, highly responsive, durable, and are able to switch between multiple uses without disruption to operations (Ruth et al., 2014). Production of hydrogen is also crucial for future energy systems since it has many possible uses. High-temperature electrolysis might provide a better interface for combining nuclear with renewables in a hybrid energy system because wind and solar photovoltaic systems generate electricity directly. This allows for the possibility of utilising heat from a nuclear reactor and most or all of the electricity from renewable sources. One such possible hydrogen interconnection is shown in Fig. 5 (Orhan et al., 2012). Few other studies (Al-Zareer et al., 2017; Ozcan and Dincer, 2016) have also been reported on nuclear energy based integrated system for hydrogen production and their thermodynamic modelling shown good efficiency.

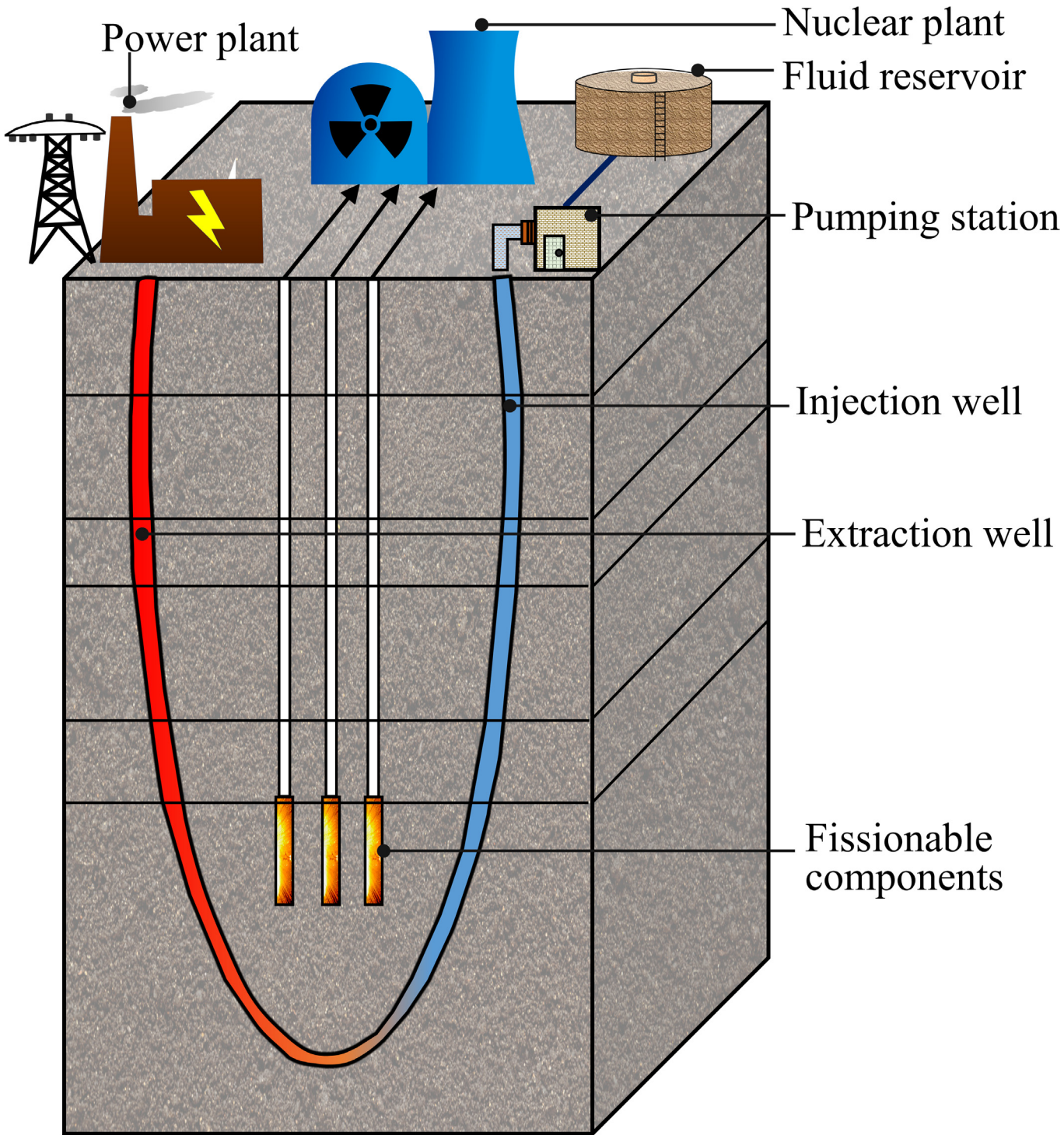

Fig. 3. Hybrid nuclear-geothermal energy system.

4.3. *Benefits of hybrid energy systems*

The proposed integrated nuclear-renewable energy systems can offer a lot of advantages, few of them are as follows (Bragg-Sitton et al., 2014):

- Greenhouse gas emission will be reduced and the phenomenon of global warming can be mitigated.
- Helps in making renewable energy highly competitive and cleanly extends green energy for generations.
- Intermittent renewable energy can have high grid penetration by renovating the grid infrastructure to provide grid-scale energy storage and dispatch.
- Setting out of advanced integration via smart control and heat management technologies will enable increased energy conversion efficiency.

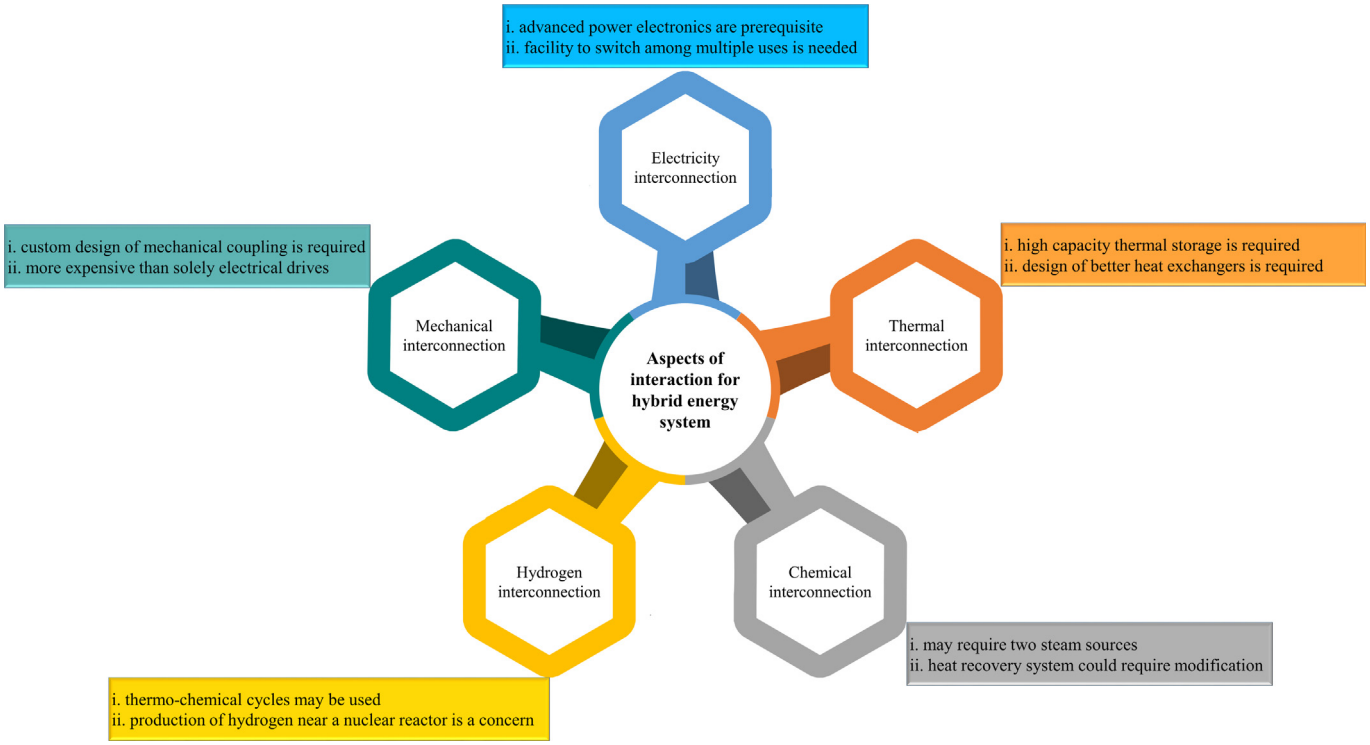
i. advanced power electronics are prerequisite
ii. facility to switch among multiple uses is needed
Electricity interconnection
i. custom design of mechanical coupling is required
ii. more expensive than solely electrical drives
Mechanical interconnection
Aspects of interaction for hybrid energy system
Thermal interconnection
i. high capacity thermal storage is required
ii. design of better heat exchangers is required
Hydrogen interconnection
Chemical interconnection
i. may require two steam sources
ii. heat recovery system could require modification
i. thermo-chemical cycles may be used
ii. production of hydrogen near a nuclear reactor is a concern

Fig. 4. Different possible ways of interaction for nuclear-renewable systems.

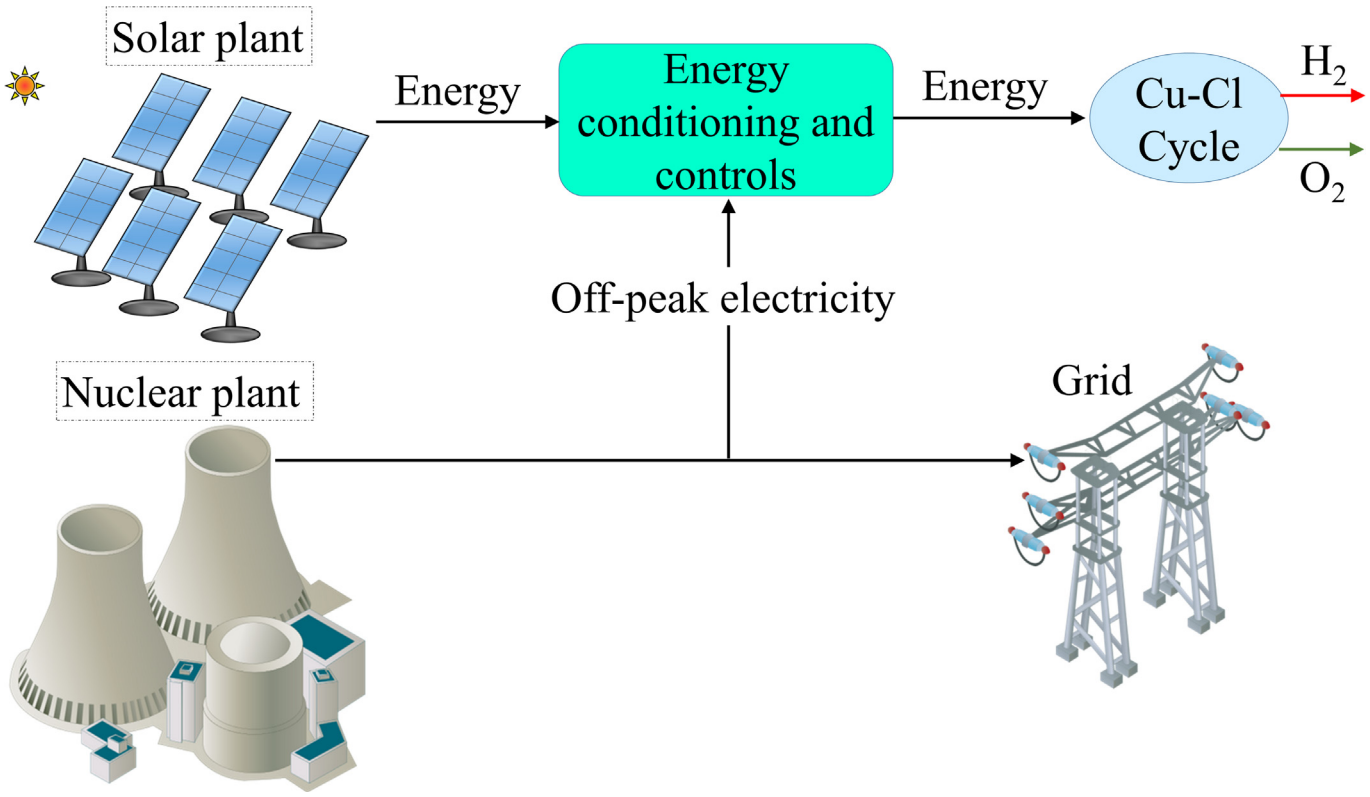

Fig. 5. Schematic of nuclear-assisted solar-hydrogen generation.

- Economical, highly reliable supply of electricity and consistent power can be generated in addition of other supplementary services to the grid.
- Hybrid energy systems are capable of producing biofuel, synfuel or hydrogen which can reduce the dependence of the transportation sector on fossil fuels.

- Overcomes the unease and psychological fear associated with nuclear power by going hand in hand with renewable energy having high public support.

It is important to emphasise here that few of the advantages mentioned for hybrid system are similar to the individual energy generation system; however, the big leap comes in terms of overcoming intermittency of renewable energy and attenuate adverse public opinion about nuclear. Efficiency of the integrated nuclear-renewable systems also get increased drastically. Moreover, it also helps in not stressing any particular resource's infrastructure beyond the threshold level in a given timeframe, and thus keep pricing and other factors in control. For example, if only solar-photovoltaic is used, the rare-earth materials like cadmium used in its manufacturing can distort the market dynamics.

4.4. Economics, status, and challenges

Apart from environmental concerns, commercialisation of any energy system is crucially dependent upon return on investment within a timeframe. Sabharwall et al. (2015) concluded that— on comparing the economics of three cases: nuclear power plant, integrated nuclear-wind facility, and a nuclear-wind system with hydrogen production facility—after optimisation nuclear, wind, and hydrogen production could lead to faster returns on investment, thus making nuclear-renewable hybrid energy systems an economically attractive option for the future.

Even though, recently hybrid solar and gas power plant began operation in Germany, the hybrid nuclear-renewable energy systems are in its nascent stage. Despite the fact that various nuclear-renewable systems are under different stages of development at present, a common status of them may be described as shown in Fig. 6. Presently, search of funding and partners are in progress for most of them.

Consideration of energy generation routes having closely coupled or integrated energy systems is not new; however, integration of nuclear and renewable sources in this way for achieving the goal of sustainability, low carbon emissions, and energy security is novel one. The paths of designing, developing, and deploying a closely integrated nuclear-renewable energy system have various trials waiting for. Broadly, these challenges may be categorised as follows (Bragg-Sitton et al., 2014; Ruth et al., 2014; Sabharwall et al., 2015):

Integration Value: There is a likelihood of increase in the cost of components of the integrated energy systems. There will be an extra risk or concern of increasing the efficiency and energy accessibility, else the integrated nuclear-renewable system will not be adopted and just will remain a concept. A flexible grid specific to such integrated system should also be provided by market structures without looking for much profit in the beginning.

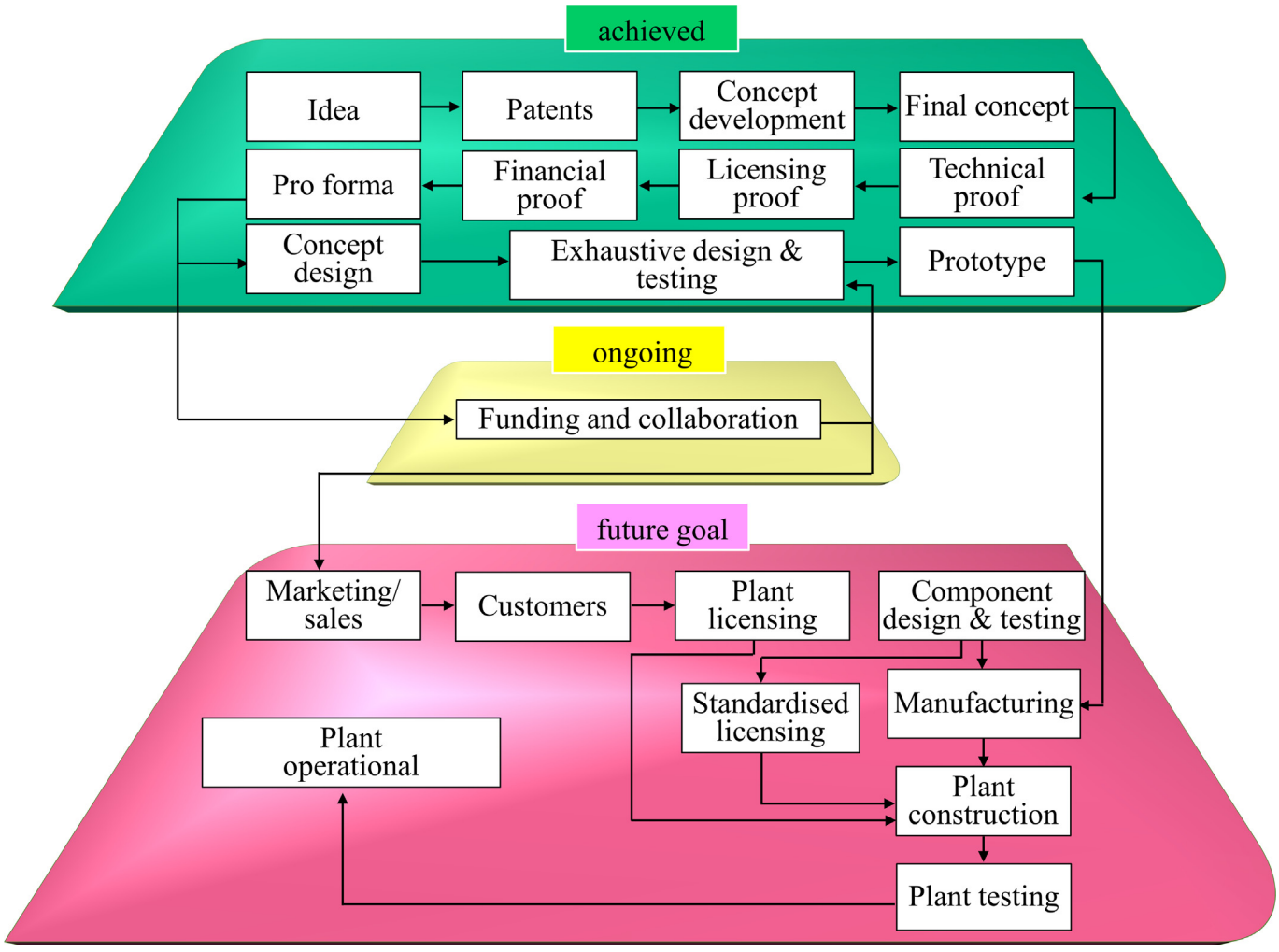

Fig. 6. Status of hybrid nuclear-renewable energy systems.

Technological: An integrated energy system presents challenges in interfacing multi-component of various subsystem. There is also a need of developing cutting-edge equipment for controlling and reliable power generation. Adaptation of these technologies with a commercial readiness coupled with safety assessments will be also the key for the success of integrated energy systems.

Financial: Such integrated energy systems require huge initial investment overall and for that there is a need to develop a new business model. Agreements regarding risk, profit and various other issues need to be discussed between financers and operators of the integrated energy system. Trends of energy market need to be closely monitored and declaration regarding optimal capital utilisation should be given.

Regulatory: Policy makers should recognise nuclear plants alongside other utilities generating large amounts of wasted heat. International cooperation programs involving both nuclear and heat stakeholders should be encouraged (Leurent et al., 2017). Since no such systems exist, there is a need to set up a new regulatory board that will frame new policies and guidelines, and provide license for the operation. There may be the need for the involvement of multiple regulatory agencies for each subsystem and their interfacing. New regulations, re-regulation, or deregulation may be needed for the electrical and various other energy establishments.

5. Conclusions

Nuclear-renewable hybrid energy systems are integrated facilities comprised of nuclear reactors, renewable energy generation, and industrial processes that can simultaneously address the need for grid flexibility, greenhouse gas emission reductions, and optimal use of investment capital. This review article summarises various aspects of nuclear-renewable energy systems in detail, apart from briefly highlighting the present scenario of energy generation, and concerns associated with nuclear and renewable energy sources while operating independently. Following conclusions may be drawn based on the present study:

- It may be speculated that integrating nuclear energy and renewable energy into a single hybrid energy system, coupled through informatics linkages, would enable to overcome the demerits of these two carbon-free energy sources while operating as independent power generation system.
- Renewables are intermittent but highly subsidised by funding agencies and readily accepted by public while nuclear has high capacity factor but little public trust at present. Evolving and bringing these two energy generation routes together will not only make power production continuous but also ease the apprehensions of people reserved for nuclear.
- Such hybrid systems provide alternative for the production of other clean energy sources like hydrogen during off-peak periods.

Even though fully integrated nuclear-renewable hybrid systems have not yet been commercialised, the component technologies are mature and waiting for funding opportunities to go for start-ups. In order to commercialise hybrid energy systems, technical development, systems analysis, and optimisation of the concepts are necessary. However, the development of such systems is both a technical and policy challenge because such hybrid energy systems cut across the traditional corporate, government and regulatory structures designed for single energy sources.

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